A Glitch in an Anomalous X-ray Pulsar

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ABSTRACT

We report the detection of a sudden spin-up of the 11 s anomalous X-ray pulsar 1RXS J170849.0−4000910 in regular timing observations made with the *Rossi X-ray Timing Explorer*. The event, which occurred between MJD 51446 (1999 September 25) and 51472 (1999 October 21), is well characterized by an increase in the rotational frequency of magnitude $|\Delta\nu/\nu| = (6.2 \pm 0.3) \times 10^{-7}$ and an increase in the rate of spin down $|\Delta\dot{\nu}/\dot{\nu}| = (1.38 \pm 0.25) \times 10^{-2}$. These values are very similar to those of glitches observed in the Vela radio pulsar and other young radio pulsars. The event therefore suggests that the internal structure of this anomalous X-ray pulsar is similar to those of the radio pulsars. In particular, it implies that the fractional moment of inertia in neutron superfluid that is not corotating with the crust is $\geq$1%. The detection of a glitch in this anomalous X-ray pulsar constrains models for the origin of glitches in neutron stars. Most notably, it challenges models that preclude glitches in long-period pulsars, and, under the magnetar hypothesis, suggests that large glitches can occur in hot neutron stars. The glitch is consistent with the predictions of the magnetar model for anomalous X-ray pulsars, but accretion-powered scenarios cannot be excluded using our observations alone.

Subject headings: stars: neutron — Pulsars: individual (1RXS J170849.0−4000910) — X-rays: stars

1. Introduction

An unusual class of X-ray pulsars, the anomalous X-ray pulsars (AXPs), has been puzzling since the discovery of the first such object some 20 years ago (1E 2259+586, Fahlman

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& Gregory 1981). AXPs are characterized by spin periods in the range of 5–12 s, steady spin down, X-ray luminosities greatly exceeding their inferred spin-down luminosities, steep X-ray spectra, and lack of evidence for a binary companion, either optically or from Doppler shifts (Mereghetti & Stella 1995, van Paradijs, Taam, & van den Heuvel 1995). All five known AXPs are located in the Galactic Plane, and two are coincident with supernova remnants (Fahlman & Gregory 1981, Gotthelf & Vasisht 1998). A sixth AXP candidate is also at the center of a supernova remnant (Gaensler, Gotthelf, & Vasisht 1999).

Two main models have been suggested to explain the nature of the AXPs. The lack of evidence for companions and their location in the Galactic plane as well as in supernova remnants suggests that AXPs are young, isolated neutron stars. In this case, the steady spin-down, under the assumption that it is due to magnetic dipole braking as in radio pulsars, implies surface dipolar magnetic fields of $10^{14} - 10^{15}$ G. Such fields are similar to those inferred independently in the soft gamma repeaters; both classes of object have therefore been suggested to be "magnetars" (Duncan & Thompson 1992, Thompson & Duncan 1995, Thompson & Duncan 1996, Kouveliotou et al. 1998, Kouveliotou et al. 1999). The large X-ray luminosities of the AXPs in this model may arise from energy from the decay of the large magnetic field (Thompson & Duncan 1996) or from enhanced thermal emission (Heyl & Hernquist 1997).

Alternatively, it has been proposed that AXPs are accreting neutron stars, with either (i) a very low-mass companion (Mereghetti & Stella 1995) or (ii) with no companion, but with accretion disks perhaps made of material leftover after a companion was disrupted (van Paradijs, Taam, & van den Heuvel 1995), or, for a young neutron star, material remaining from the supernova explosion (Chatterjee, Hernquist, & Narayan 2000, Perna, Hernquist, & Narayan 2000, Alpar 1999). In this case, the X-ray luminosity is from accretion, and the prolonged spin-down is a result of the pulsars being close to their equilibrium spin period or of them being in an extended "propeller" regime of centrifugal expulsion (Chatterjee et al. 2000, Alpar 1999).

One way to discriminate among these models is through timing observations. In the magnetar model, timing irregularities and sudden spin-up events, as are seen in the young radio pulsar population, are expected (Thompson & Duncan 1996), but long episodes of spin-up should not be seen. Also, a long-term periodicity superimposed on the spin-down might be expected due to radiative precession (Melatos 1999). By contrast, in an accretion scenario, large random torque fluctuations could be expected, as might extended episodes of spin-up (Baykal & Swank 1996, Chakrabarty et al. 1997, Bildsten et al. 1997).

Past timing observations of AXPs have been hampered by poor sampling, such that multiple interpretations of the same data set were possible (e.g. Usov 1993, Heyl & Hernquist

1999, Melatos 1999). Kaspi, Chakrabarty & Steinberger (1999) [hereafter KCS99] showed that with monthly observations, phase-coherent timing of at least two AXPs (1E 2259+586, 1RXS 1708−4009) was possible, demonstrating that the AXPs can be very steady rotators and that such monitoring observations can in principle distinguish among models.

Here we report on continued monitoring of the 11-s AXP 1RXS J170849.0−400910 (hereafter 1RXS 1708−4009) with the *Rossi X-ray Timing Explorer* (*RXTE*). We show that although 1RXS 1708−4009 rotated extremely steadily for nearly 2 yr, a sudden spin-up event occurred between two observations at epochs MJD 51446 and 51472. We show that the properties of the event are very similar to the "glitches" seen in young radio pulsars.

2. Observations and Results

The *RXTE* observations described here are a continuation of those reported by KCS99. We refer the reader to that paper for details of the analysis procedure. Briefly, all observations were obtained with the Proportional Counter Array (Jahoda et al. 1996), with events in the range 2.5–5.4 keV selected to maximize signal-to-noise ratio. Data have been obtained roughly monthly since 1998 January and were reduced using software designed to handle raw spacecraft telemetry packet data. They were binned at 62.5 ms resolution and reduced to the solar system barycenter in barycentric dynamical time using the JPL DE200 solar system ephemeris.

The spacing of the observations was carefully chosen to permit absolute pulse phase determination using standard radio pulsar techniques. The timing ephemeris of KCS99 was the starting point in the continuing analysis, with individual observations folded at the predicted barycentric period. A total of 64 pulse phase bins were used. Folded profiles were cross-correlated in the Fourier domain with a high signal-to-noise ratio average profile in order to determine an average pulse arrival time. Resulting arrival times were then analyzed using the TEMPO pulsar timing software package.[4]

The ephemeris given by KCS99, which was determined from 19 observations made in the interval MJD 50826 – 51324 (1998 January 13 – 1999 May 26), continued to predict phase for over 120 days, until MJD 51446 (1999 September 5). This is clear from the pre-glitch timing residuals (see Figure 1) which have RMS 130 ms ($0.012P$, where $P = 1/\nu$ is the pulse period). The subsequent observation, on MJD 51472 (1999 October 21), was not well-predicted, and the following residuals grew steadily (see Figure 1a). For this reason, we initiated a pre-

[4]http://pulsar.princeton.edu/tempo

planned series of three closely spaced observations in order to independently determine the new pulse frequency ν. All observations from MJD 51472 onward are well modeled by a single ν and $\dot{\nu}$. This revised ephemeris has now properly described 9 arrival times obtained over 142 days, with RMS residuals of only 71 ms ($0.006P$). Table 1 summarizes the spin parameters before and after the event, where the values are extrapolated to MJD 51459, the midpoint between MJDs 51446 and 51472. Residuals after subtraction of the pre-glitch model from the pre-glitch data and the post-glitch model from the post-glitch data are shown in Figure 1b.

The frequencies given in Table 1 imply that the pulsar suddenly spun up, with fractional frequency change $|\Delta\nu/\nu| = (6.2 \pm 0.3) \times 10^{-7}$. Furthermore, following the event, the spin down rate increased in magnitude by $|\Delta\dot{\nu}/\dot{\nu}| = (1.38 \pm 0.25) \times 10^{-2}$. In both cases, the uncertainties are derived by combining those of the pre- and post-glitch values in quadrature. These changes are very similar to those observed in the Vela radio pulsar, as well as in other radio pulsars of "adolescent" age (e.g. McKenna & Lyne 1990, Kaspi et al. 1992, Shemar & Lyne 1996, Lyne et al. 1996, Wang et al. 2000; see §3).

Although the timing event is well described by a simple step function model, it can in principle also be described by a continuous model with a single $\nu, \dot{\nu}$ and significant $\ddot{\nu}$. However, in this case, the timing residuals show strong systematic trends, including a clear discontinuity at the epoch of the event, and the RMS residual is approximately three times larger than that in the pre-glitch model. Smooth deviations from a simple spin-down law have been observed in many, if not most radio pulsars and are known as "timing noise" for lack of a better term. However, discrete events like the one we have observed for 1RXS 1708−4009, especially since they are always observed to be sudden spin-ups, are a distinct phenomenon classified as glitches (see Lyne 1996 for a review). The identification of discrete events as a distinct phenomenon in radio pulsars has grown out of many years of phase-coherent timing observations of hundreds of sources, something unavailable for AXPs. Thus, by the conventional operational definition for glitches in radio pulsars, and by Occam's Razor, we conclude that the timing event we have observed in 1RXS 1708−4009 is indeed a glitch. However, it should be kept in mind that it may instead represent a new phenomenon not seen in radio pulsars. Only continued timing observations will settle this point with certainty.

We detected no change in the 2.5–5.4 keV X-ray flux from the pulsar at the time of the glitch. We set an upper limit on flux variations of $<20\%$ (3σ) of the mean flux. We also detected no statistically significant change in the X-ray pulse profile at the time of the glitch.

3. Discussion

The spin-up event we have observed in 1RXS 1708−4009 is very similar to the glitches seen in the Vela radio pulsar and other radio pulsars of comparable age, that is, with $10^4 < \tau_c < 10^5$ yr, where characteristic age $\tau_c \equiv P/2\dot{P}$ (e.g. Shemar & Lyne 1996, Wang et al. 2000). In such young pulsars, observed glitches are dominated by frequency steps of size $\Delta\nu/\nu \simeq 10^{-7} - 10^{-6}$. Furthermore, such glitches frequently show increases in the magnitude of the spin-down rate of order a few percent, sometimes, but not always, with subsequent relaxation back to the pre-glitch value on time scales of several hundred days. The rates of occurrence of such glitches vary from source to source, with some occurring more frequently than once per year (e.g. PSR J1341−6220, Kaspi et al. 1992, Wang et al. 2000), and most (generally the older pulsars, $\tau_c \gtrsim 50$ kyr), never having been observed to glitch. All these properties are consistent with those of the spin-up event in 1RXS 1708−4009 ($\tau_c = 9$ kyr), namely the magnitude of the glitch, the change in the slow-down rate, and even, very crudely, the rate of occurrence, once per ~ 2 yr of observation. Some glitching radio pulsars, especially the well-studied Vela pulsar, have also shown significant relaxation on time scales of hours to days (e.g. Chau et al. 1993). However, such behavior is on too short a time scale to be detectable in our observations of 1RXS 1708−4009.

Large glitches in radio pulsars have been ascribed to sudden unpinning of superfluid neutron vortices (Anderson & Itoh 1975, Alpar, Cheng, & Pines 1989, Alpar et al. 1993). The neutron star spins down under the influence of an external torque which acts on the crust. For radio pulsars, the torque is magnetic dipole braking. Neutron superfluid in the stellar interior, which is not well coupled to the crust, has its angular momentum carried in quantized vortices. The superfluid can spin down by outward motion of these vortices. However, vortex line pinning to crustal nuclei can impede their outward motion. The crust and superfluid components therefore develop a differential angular velocity. Occasionally, sudden unpinning of vortex lines can occur, and the previously decoupled superfluid can spin down, transferring angular momentum to the crust in the process. A spin-up event is therefore observed. The neutron superfluid thus acts as an angular momentum reservoir to fuel glitches. The similarities in the properties of the spin-up event seen in 1RXS 1708−4009 to those seen in the Vela-like pulsars suggests that a similar mechanism is at work in 1RXS 1708−4009.

In contrast, smaller glitches observed in the younger Crab pulsar are dominated by changes in spin-down rate rather than in pulse frequency (Lyne, Pritchard, & Smith 1993). These are ascribed to changes in the neutron star ellipticity due to cracking of the crust. The magnitude and frequency of the Vela-like glitches are incompatible with such a model but agree well with the vortex-line unpinning model, in which the fractional angular momentum change per glitch is roughly constant from source to source (Alpar & Baykal 1994).

From the observed glitch parameters, we can estimate the fraction of the neutron star moment of inertia in neutron superfluid that is not corotating with the crust, I_s. First, one can show (e.g. Link, Epstein, & Lattimer 1999) that

$$\frac{I_s}{I_c} \geq \frac{\overline{\nu}}{|\dot{\nu}|} A, \tag{1}$$

where I_c is that of the crust and all other coupled components, $\overline{\nu}$ is the average spin frequency over the observing span, and A is the activity parameter (McKenna & Lyne 1990), where

$$A = \frac{1}{t} \sum_i \frac{\Delta\nu_i}{\nu}. \tag{2}$$

Here, t is the observing span, and the sum is over all observed glitches. As we have observed only one glitch for 1RXS 1708−4009, we can only crudely estimate A, under the assumption that we were not extremely lucky in detecting the glitch, and perhaps also that the small value of $\ddot{\nu}$ observed before the glitch (KCS99) was due to relaxation following a glitch that occurred before our observations began (cf. Lyne et al. 1996). Hence, we take $t \sim 3$ yr, so $A \sim 5 \times 10^{-7}$ yr^{-1}(3 yr$/t$), and $I_s/I_c \geq 0.01(3$ yr$/t)$, similar to that found for many Vela-like pulsars (see Link, Epstein, & Lattimer 1999 and references therein). Alpar et al. (1993) suggested a different estimate for I_s, namely $I_s/I_c \geq \Delta\dot{\nu}/\dot{\nu}$, where short-term transient contributions to $\Delta\dot{\nu}$ have been omitted. Since we were not sensitive to short time scale transients, our measured $\Delta\dot{\nu}$ can be used directly, and yields $I_s/I_c \geq 0.01$, consistent with the first estimate.

Thus, the glitch implies that I_s in 1RXS 1708−4009 is similar to that in the Vela-like pulsars. We note, as pointed out to us by I. Wasserman (personal communication) that this renders models of long time-scale precession in AXPs (Melatos 1999) unlikely, because of the expected dynamics of the superfluid interior (Shaham 1977, Alpar & Ögelman 1987).

Ruderman, Zhu & Cheng (1998) have suggested that the origin of the vortex line unpinning events is cracking of the neutron star crust under stresses imposed by outward-moving magnetic flux tubes. These tubes move because they interact with the outward-migrating angular momentum vortex lines as the neutron star spins down. However, this model predicts that glitch activity should be absent in neutron stars having $P \gtrsim 0.7$ s because the vortex motion is too slow to cause the necessary stresses. This is in contradiction with the large glitch in the 11-s 1RXS 1708−4009. Thus our observations suggests that the Ruderman et al. (1998) model is inapplicable to the glitch in 1RXS 1708−4009. Given the similarity of this event to those seen in Vela-like pulsars, this may cast doubt on the relevance of the model to those sources as well.

Usov (1993) and Heyl & Hernquist (1997) argued that spin-down irregularities in other AXPs (1E 2259+586 and 1E 1048.1−5937) are also due to glitches. The data they used did not involve phase coherent observations as did ours, and so their conclusions are much less certain. Furthermore, the fractional amplitude of the glitches they inferred are several orders of magnitude larger than what we have observed for 1RXS 1708−4009. Given the glitch in 1RXS 1708−4009, one might suspect that the previous claims of glitches in other AXPs were correct. However our ongoing observations of AXPs 1E 2259+586 and 1E 1048.1−5937 do not support the conclusion that the timing irregularities in those objects are due to sudden spin-up events. A detailed discussion of these sources will be presented elsewhere.

Glitches in AXPs were predicted in the magnetar model (Thompson & Duncan 1996). These authors argued that crust fracture and superfluid vortex line unpinning play a major role in outbursts of soft-gamma repeaters (SGRs), and are ultimately due to the stresses imposed on the crust by the large magnetic field. However, the glitch alone does not provide proof of the magnetar hypothesis. The origin of neutron-star glitches in the vortex-line unpinning models is independent of the source of the external torque acting on the crust. Rather, it relies upon an angular velocity differential between the crust and that portion of the superfluid that is effectively decoupled from the crust.

It has been argued (Ruderman 1976, Alpar, Nandkumar, & Pines 1985, Ruderman 1991) that the different nature of the glitches in the very young Crab pulsar (τ_c = 1 kyr, Lyne et al. 1993) and the absence of glitches in the young PSR B1509−58 (τ_c = 1.6 kyr, Kaspi et al. 1994) imply that giant glitches do not occur in the youngest pulsars because they have higher internal temperatures, which allow a more plastic flow of vortex lines. However, in the magnetar model, the X-rays are a result of thermal processes, either magnetic field decay (Thompson & Duncan 1996) or enhanced thermal emission from initial cooling (Heyl & Hernquist 1997). In either case, the neutron star is very hot. This is supported by the X-ray spectrum of 1RXS 1708−4009: it can be fit with power-law and blackbody components (although the latter is not strictly required), which suggest a surface temperature of $kT \simeq 0.4$ keV (Sugizaki et al. 1997). This is hotter than is observed in any of the Vela-like pulsars, and higher than expected in the very youngest pulsars for all cooling models (Ögelman 1995), even if the measured temperature is an overestimate of the true surface temperature because of atmospheric effects (e.g. Meyer, Pavlov, & Mészáros 1994). Thus, in the magnetar model, the glitch in 1RXS 1708−4009 argues that the differences in the glitching behavior of the youngest radio pulsars compared to the "adolescent" Vela-like pulsars may not be primarily due to the difference in internal temperature.

In the recently proposed AXP model in which these sources are accreting from disks of material formed after the supernova explosion (Chatterjee et al. 2000, Perna et al. 2000, Alpar 1999), the spin-down rates are a result of accretion torque, which presumably acts only on magnetic field lines anchored in the crust. Thus, glitches might be expected in this model as well. In this case, the frequent glitches seen in Vela-like pulsars might be less influenced by their age than by their relatively large spin-down rates. A prediction of this hypothesis, independent of AXP phenomenology, is that glitches occur in neutron star X-ray binaries, although large fluctuations in accretion torque (e.g. Bildsten et al. 1997) make them difficult to detect. The low-mass X-ray binary 4U 1626−67, in which the spin-down is extremely stable apart from episodes of sudden torque reversal (Chakrabarty et al. 1997), should be an excellent candidate for the detection of glitches, although none has been seen in $\sim$5 yr of timing using the BATSE instrument.

Recent deep infrared observations of the field containing the AXP 1E 2259+586 (Hulleman et al. 2000) have not detected any emission from a putative accretion disk, casting some doubt on the fallback disk model. If 1RXS 1708−4009 is indeed isolated, however, the glitch is consistent with the magnetar model, which provides the required external torque via magnetic dipole braking. However, since constraining optical/infrared observations of the 1RXS 1708−4009 field have yet to be done, an accretion scenario for this source cannot be ruled out.

Finally, glitches will complicate the determination of braking indexes in AXPs as well as the search for periodic variations in the spin period predicted in the magnetar model due to precession. Nevertheless, continued long-term monitoring of 1RXS 1708−4009 is essential for the determination of the amplitude distribution and frequency of its glitches. Similar observations of other AXPs are necessary to determine whether glitch behavior is ubiquitous.

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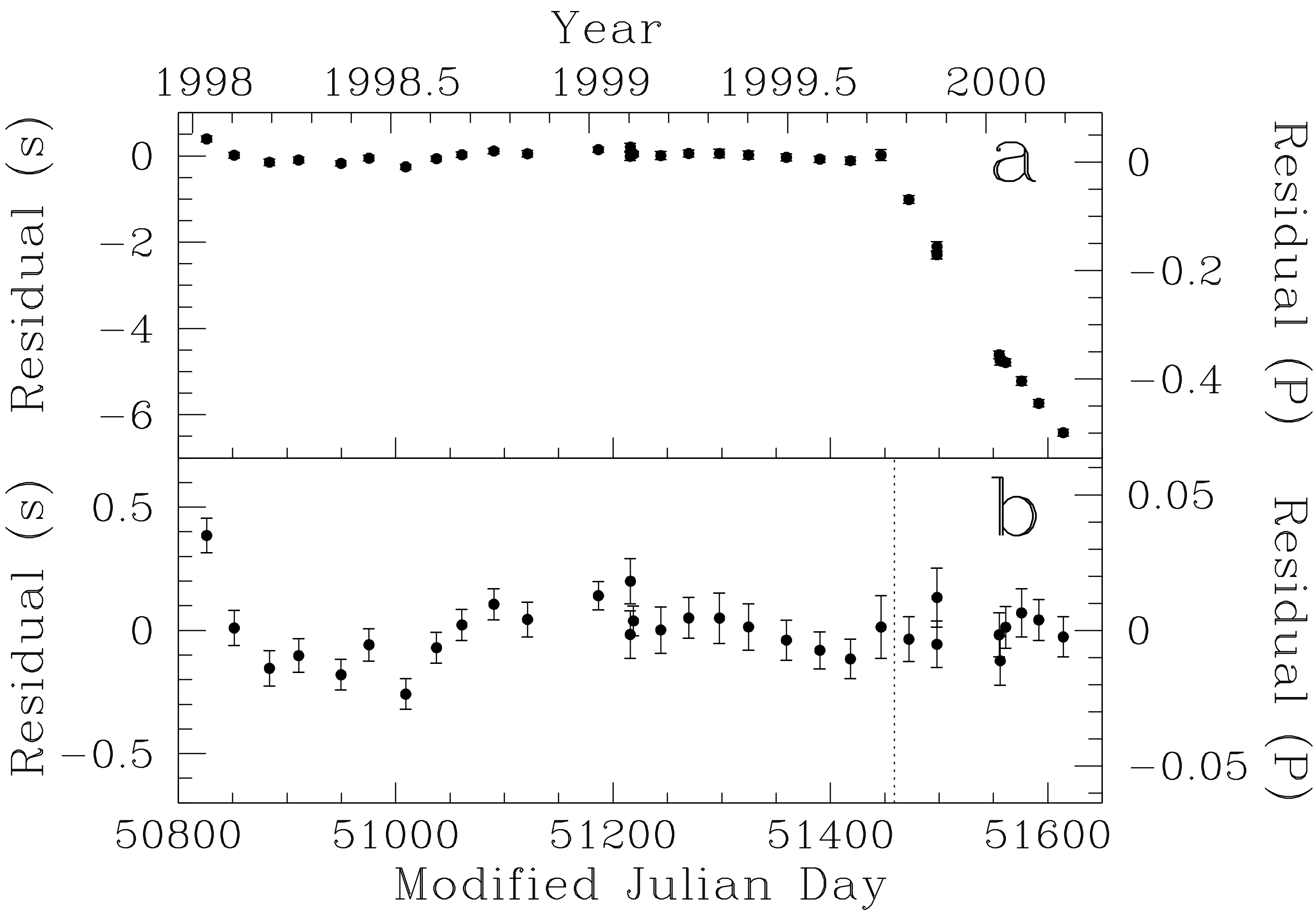

Fig. 1.— Timing residuals for 1RXS 1708−4009. (a) Residuals after subtraction of the pre-glitch model from all pulse arrival times. The spin-up event, evident as the series of early pulse arrival times relative to the long-term spin down, occurred between MJDs 51446 and 51472. (b) Residuals after subtraction of the pre-glitch model from the pre-glitch data, and the post-glitch model from the post-glitch data (see Table 1). The dotted line indicates the pre- and post-glitch separation. Note the difference in vertical scales in (a) and (b).

Table 1. Measured Spin Parameters for 1RXS 1708−4009.

Parameter	Pre-Glitch Value	Post-Glitch Value
Spin Frequency, ν (Hz)	0.0909136408(7)	0.090913697(3)
Spin Frequency Derivative, $\dot{\nu}$ (10^{-13} s^{-2})	−1.5681(2)	−1.590(4)
Spin Period, P (s)	10.99944949(8)	10.9994427(3)
Spin Period Derivative, $\dot{P}$ (10^{-11})	1.8972(3)	1.9241(48)
Epoch (MJD)	51459.0	51459.0
RMS Timing Residual (ms)	130	71
Number of Arrival Times	23	9
Start Observing Epoch (MJD)	50826	51472
End Observing Epoch (MJD)	51446	51614

Note. — Numbers in parentheses represent 1σ uncertainties in the last digit quoted.